Tests on Tile Vaults in France in the 19th Century

Esther Redondo Martínez
Department of Building Technology, Universidad Europea de Madrid, Spain

Tile vaults are a construction system in which bricks are laid flat, usually in two layers. Its origin is uncertain; precedents exist from very early dates in various places around the Mediterranean sea. From the 16th to the 20th century we find numerous examples in Spain, Italy, the south of France and some countries in North Africa. Throughout the 19th century, the construction of tile vaults experienced important development tied to the emergence of new building types, industrial buildings in particular. These new types required fireproof structures, and brick was at a great advantage over timber in this respect.

The use of cement as a binder spread during the 19th century. The appearance of this new material was decisive in the development of the tile vault. In contrast with the plaster used until then, rapid cement also hardens in short time but does not suffer alterations with the degree of damp, nor does it increase in volume as it sets. On the other hand, it re-ignited a debate latent since the mid 18th century about the monolithic behaviour of these vaults, where monolithic behaviour is defined as having no thrust transferred to the supports.[1] And finally, the 19th century is a period in which two trends of thought converge: a trend continuing from the past [great vault builders who worked following common rules of proportion] and the current trend, in which everything must be sustained by a theory.

This is the historical context in which the French tests studied in this paper were carried out. These tests were looking for a theory that endorsed the building practice that had been going on for centuries and, at the same time, they aimed to assess the validity of the monolithic model explained above. In the same period [1830-1900] experiments on tile vaults were carried out in other places, in particular where this construction system was not traditional, in order to offer the necessary guarantees for its use. Guastavino, on arriving in the United States in 1881, tested his vaults exhaustively, studying both their strength and their performance under fire. Tests were also carried out in England. Even in Spain, where tile vaults were a traditional way of building floors and roofs, tests were carried out on some vaults under different conditions.[2]

In France tile vaults were traditionally built in the region of Roussillon. Both Blondel (1771) and, later, Rondelet (1802) reproduced in their influential treatises this way of construction.[3] All the French authors emphasized its fireproof nature, in contrast with the standard timber floors, as well as its monolithic behaviour that resulted from the perfect bond between bricks and plaster. They defended that if these vaults exerted thrust on the supporting walls it was solely because the plaster expands when it sets and moves the supports; should precautions be taken to avoid this, the vaults do not push at all.[4] Many tile vaults were built in France throughout the 19th century, as can be derived from numerous comments found in the texts under study.[5] Possibly because this method was not so much part of the construction tradition in France as it was in Spain and fewer built examples were available for study, more tests were carried out in order to validate the new system.

D'Olivier, 1837

D'Olivier was a military man, captain of the Engineers corps. He related his tests in an essay, "Relatif à la construction des voûtes en briques posées de plat, suivi de recherches expérimentales sur la poussée de ces sortes de voûtes," published in 1837. The essay is divided into two chapters. In the first chapter he offers a number of general considerations on the construction, many of them similar to those given by Blondel (1771). D'Olivier thoroughly insists on solving the problem of the expansion of plaster when setting[4] and for this purpose he designed a special kind of bricks he calls "à crochet" (see *Fig. A* in Fig. 1), featuring interconnected reliefs. According to his experiments, these bricks are capable of absorbing the expansion of the plaster between the reliefs: "L'expérience a confirmé ce raisonnement. Dans la construction des voûtes que j'ai fait exécuter, j'ai eu soin, pour les premières construites, de les laisser ouvertes à la clef; elles ont demeuré quatre jours en cet état, et il ne s'est pas manifesté le moindre allongement" (d'Olivier 1837, 294-295).

He describes his tests in the second chapter. The reason d'Olivier confesses for carrying out the experiments is interesting: "vu que l'on a souvent

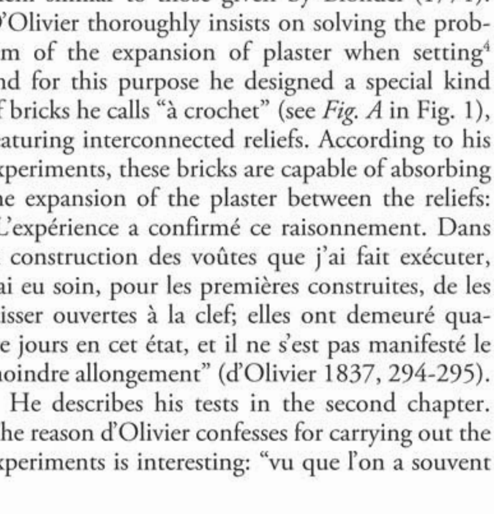

Fig. 1: Drawings of the vault tested and detail of the dynamometer and of the bricks (D'Olivier 1837, pl. 129).

dit et imprimé que ces sortes de voûtes n'avaient pas plus de poussée q'une tuile creuse posée sur une table, ou qu'un couvercle de chaudière, ce qui est une erreur qui a occasionné l'écroulement de plus d'un édifice, et qu'il importe de réfuter" (d'Olivier 1837, 304).

He performed the experiments on a double-layer vault built with his special bricks, bonded with plaster. The vault had a span of 4.89m., a length of 29cm, a rise of 47cm, and an overall thickness of eight cm (see *Fig. B* in Fig. 1). The supports could be fixed or allowed to have horizontal movement. During the construction of the vault the supports were fixed. On removing the centering, they were free to move, two intermediate dynamometers were placed on either side to apply a known force. If the thrust of the vault is greater than the force exerted by the dynamometers the supports will move.

The test consists of slowly reducing the force on the dynamometers until the vault begins to move. It starts with a force of 55kg in each dynamometer [110kg on each support and 220kg in total on the four supports], and the vault stays intact. Each force is then reduced to 50kg, obtaining the same result. When the force is reduced to 45kg the supports move slightly, cracking open at the crown, which goes down by two cm. Equilibrium is reached again with the dynamometers registering 55kg. The test continues on a new vault, so as not to superpose problems on the previous one. A force of 40kg is set in each dynamometer and the supports are left free. The supports spread and the vault collapses.

D'Olivier describes the failure process of the vault, through the formation of five hinges: one at the crown and two located at 65cm from the crown at either side form on the extrados, and two further hinges at the supports form on the intrados: "Il s'établit un mouvement de rotation autour des arêtes extrados des parties rompues, et autour des arêtes intrados des deux naissances" (d'Olivier 1837, 308). The vault thus breaks into four pieces. At the instant preceding the failure, the crown has gone down by 21cm and each dynamometer measures a force of 86.25kg.

D'Olivier concludes that the vault will be in equilibrium if every support is able to provide a force of 100kg. He generalizes the data by dividing the value by the 29cm length of the vault, obtaining a thrust of 345kg/m. at each support. From this data, he calculates the thickness of a wall [taken to have an overall height of five m., with the springing of the vault located at a height of four m., and a specific gravity of 2200kg/m.[3]] required for the vault to maintain strict equilibrium, obtaining a value of 0.50m. He admits that he has only taken the self weight of the vaults into account in these calculations [when in practice the haunches are typically filled and there is flooring on top].

He repeated the test fixing one of the supports and allowing the other one to move. D'Olivier does not elaborate as much on this second test. He only comments on the collapse mechanism: three hinges form, two of them on the intrados at the springings and the third one on the extrados at a point located 65cm from the crown in the direction of the fixed support. The vault thus breaks into two fragments.[6]

Analysis of d'Olivier's test

The essay ends with a description of the test. There is no analysis of the results, nor are they related to the theory of vaults, which, by 1837, had reached a certain level of development.[7] D'Olivier concludes that, thanks to the data obtained, it is possible to predict the thrust of similar vaults, which are the most common type of tile vault in construction. Furthermore, he states that to obtain the thrust of vaults with different shapes or sizes, similar tests can be performed.

Applying an equilibrium analysis to the vault as tested: "On the initial geometry of the vault [see Fig. 2], with the thrust given by d'Olivier as the "equilibrium" value, that is to say, 100kg at each support, the line of thrust obtained lies outside the vault. Since this line must go through the hinged supports, the maximum distance between the thrust line and the middle-axis of the arch is found at the crown, and has a value of 56.5cm. The vault then carries a bending moment of 100kg x 0.556 = 56.5 kg·m. This implies a maximum tensile stress [for a resistant cross section of 29x8cm] of 18.3kg/cm^2."[8] A similar analysis can be done on the deformed geometry of the vault the instant before failure. It is known that at that moment the crown has gone down by 21cm and the new position of the vault can be drawn.[10] This pronounced descent of the crown is produced by a spread of the supports of only 3.12cm, due to the small rise of the vault (see Fig. 3).

When the vault cracks, the line of thrust must go through the hinges that are created: through

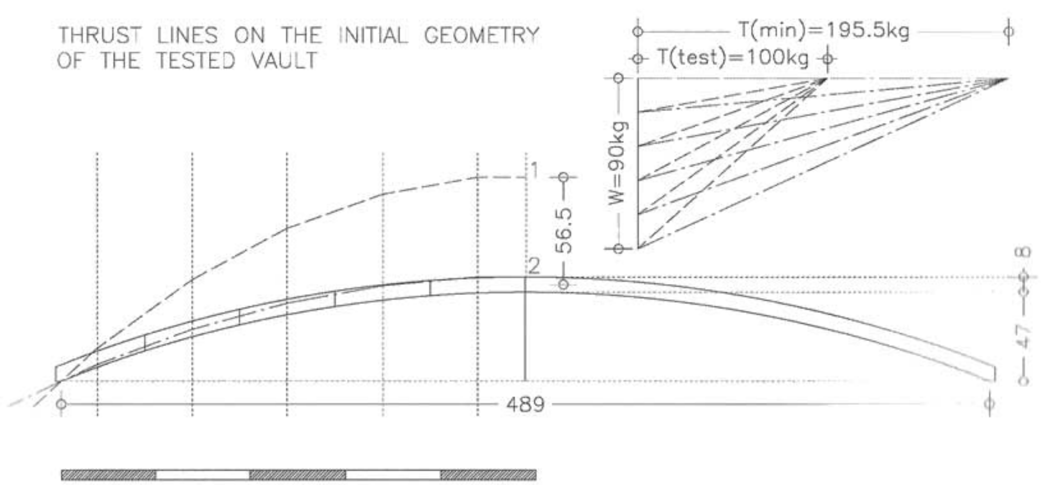

Fig. 2: Cross-section of the tested vault, initial geometry. The following thrust lines are shown superposed.9 1) [dotted line] thrust of 100 kg [proposed by d'Olivier as "equilibrium" thrust]; 2) [slash-dot line] minimum thrust line contained within the vault. It corresponds to a thrust of 195.5 kg.

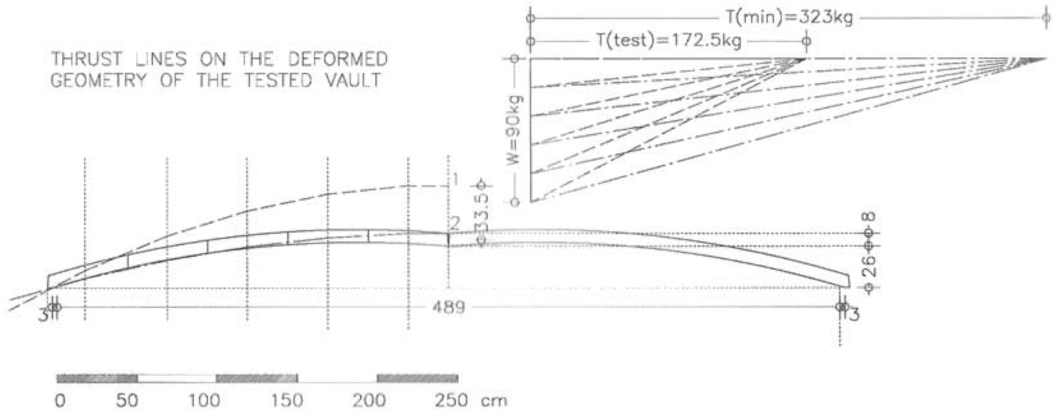

Fig. 3: Cross-section of the tested vault, deformed geometry. The following thrust lines are shown superposed. 1) [dotted line] thrust of 172.5 kg [as measured by d'Olivier the instant before failure]; 2) [slash-dot line] minimum thrust line contained within the vault. The thrust has a value of 323 kg.

the extrados at the crown and through the intrados at the springings, a configuration that corresponds to the line of minimum thrust. This minimum thrust, calculated for the deformed geometry, is 323kg, nearly double the value measured by d'Olivier in his experiment. A possible explanation for this difference could be the inadequate construction of the supports, so that friction is generated between beams A and bars E (see Fig. 4). A small horizontal force and a small bending moment would then be generated at the supports. The essay does not clearly explain how the thrust is measured, and so the difference could also be explained as an error in the measurement.

D'Olivier only published this single test,[11] applied to a vault of specific size and shape. Nevertheless, his results had a fairly large impact. In a brief construction manual (Lagarde 1849) we find a table with the thrust and the width that should be given to the supports of different small thickness brick vaults. This table, as the author indicates, has been derived from d'Olivier's test. Later on, the table was reproduced in the numerous editions of the well known treatise by Claudel and Laroque (1870, 472).

Laroque 1859

The test is included in the second edition of the treatise by Claudel and Laroque, written in 1859. Since it doesn't feature in the first edition, published in 1850, it is reasonable to date the experiment between these two years. It was carried out on a tile vault of five m. span, one m length, 50cm rise and seven cm thickness, resting on the large columns of an old building, the lazaretto of Marseille. The vault comprised two layers of bricks three cm thick, bonded with Vassy cement.[12]

Once the vault was constructed, it was loaded in a uniform way, supporting up to 45,000kg [9,000 kg/m.^{2}] without visible movement. Failure occurred under a load of 55,000kg [11000 kg/m.^{2}], related to a spread of the supports by seven mm. This test seems to be aimed at proving that this type of vault supports enormous loads provided the supports do not move: "Nul doute que la charge de rupture eût encore été plus considérable, si la forte poussée sur les points d'appui n'avait fait reculer de 0.007m dans l'intérieur d'un pilier l'une des pierres formant sommier." A vault like the one tested resists very high uniform loads, since the line of thrust is a parabola, which has the same shape as a very shallow circular arc. Under the failure load of 11,000kg/m.^{2} and with a parabolic line of thrust:

$$E = \frac{q \cdot l^2}{8 \cdot F} = \frac{11000 \quad x\, 5^2}{8\, x\, 0{,}5} = 66000\ kg/m \quad (1)$$

For this thrust, and considering a resistant cross section of 100x7 cm, the masonry is subject to 95kg/cm², a very high value close to the failure stress.[13] In this situation, a small movement of the supports [such as that of seven mm described in the test] can cause the masonry to crack.

Fontaine, 1865

Fontaine was an engineer and he carried out a number of tests in order to find the maximum load that a particular set of brick vaults could take, in order to later build a large floor surface using this type

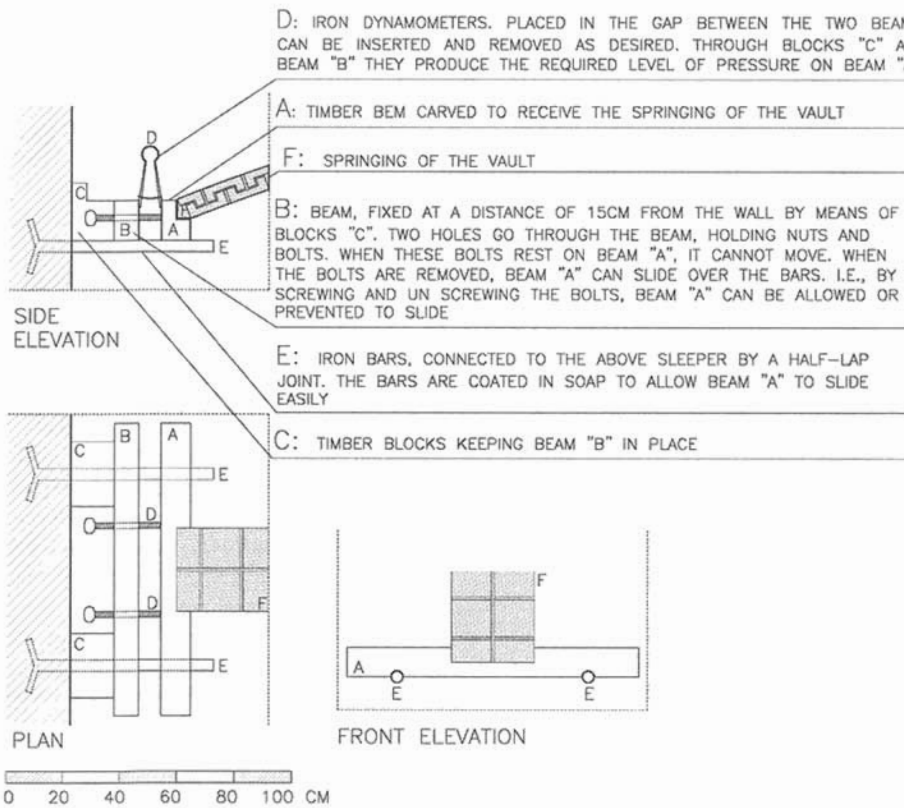

Fig. 4: Layout and description of the supporting system for the vault tested by Olivier.

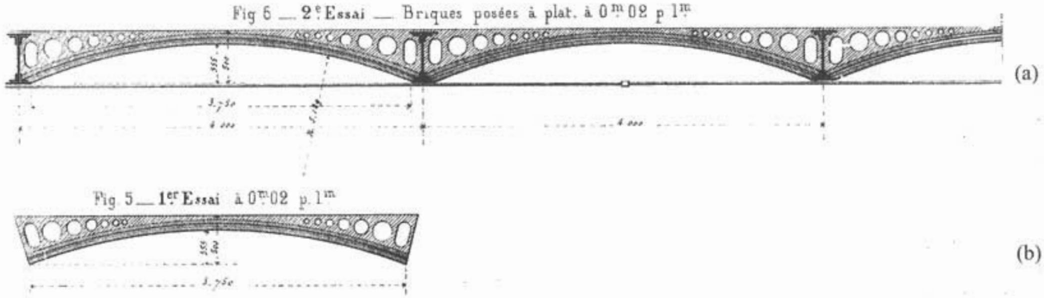

Fig. 5: Drawing of the vaults on which Fontaine performs his first and second tests (Fontaine 1865, pl 45).

of vault.[14] He published his results in an article, "Expériences faites sur la stabilité des voûtes en briques," published in 1865. Unlike d'Olivier, he begins his article with a brief description of the state of vault theory at the time, discussing primarily the concept of the line of thrust that Moseley and Méry had stated 20 years earlier and Scheffler's principle of minimum resistance.[15] Although he later applies the theory to the tested vaults, he states that he is not clear whether it is valid because the vaults are supported on flexible metallic beams and, in addition, the materials used exhibit a strong cohesion, so that the vault can be considered to be monolithic.

He performed the first test on an isolated vault with a span of 3.75m., a rise of 0.355m. and a thickness of 0.10m., comprised of two layers of cement bricks, bonded with cement (see Fig. 5, a). The vault was loaded uniformly with 2,700kg/m.^{2}, observing that it suffered no alterations under this load, even after being under the load for one month. On the contrary, the vault broke under a very small load [100kg/m.^{2}] when a weight of 200kg was thrown onto it from a height of two m. The conclusion that was extracted from this test is that a vault like this can safely support 1,000kg/m^2, but it performs poorly when subject to vibrations.

The second test was carried out on a set of three adjacent vaults (see Fig. 5, b), supported on metallic beams placed four m. apart. The geometry of the vaults was the same as that of the isolated vault of the first test, but Burgundy bricks[16] were used this time instead of cement blocks. The lateral vaults had metal ties, while the central one did not. Fontaine aimed to find out what effect could the two lateral vaults have on the central one when the former two are heavily loaded and the latter is unloaded and, in particular, to find out whether the ties were necessary.

The vaults were built and the two lateral ones were loaded progressively and uniformly, leaving the central one unloaded. When a load of 1,250kg/m.^{2} was reached, the central vault started cracking: a longitudinal crack opened along the crown and other zig-zag shaped cracks opened at the haunches. The central vault went up by 2.4cm. This load was kept constant for one night. Slowly, the central vault continued to go up, while the lateral ones went down. Finally, the lateral vaults collapsed, breaking the ties as they fell, which split in more than ten pieces, and causing very large deflections to the supporting beams. In spite of all these movements, the central vault remained standing and large forces were required to finally demolish it. The conclusion that Fontaine extracted from this experiment is that this vaulting system, comprised of two superposed layers, does not resist well the effects of large thrust against the supports.

In line with this second test, Fontaine cites the experiment performed by Laroque. Either as a result of an error in the transcription or in an attempt to show the results match his own, the failure load obtained by Laroque [11,000kg/m.^{2}] is quoted divided by ten [1,100kg/m.^{2}]. As a final conclusion to the four tests, Fontaine applies a minimum safety coefficient of two to the failure loads and states that: an isolated vault of four m. span, 1/10 rise and ten cm thickness can be loaded

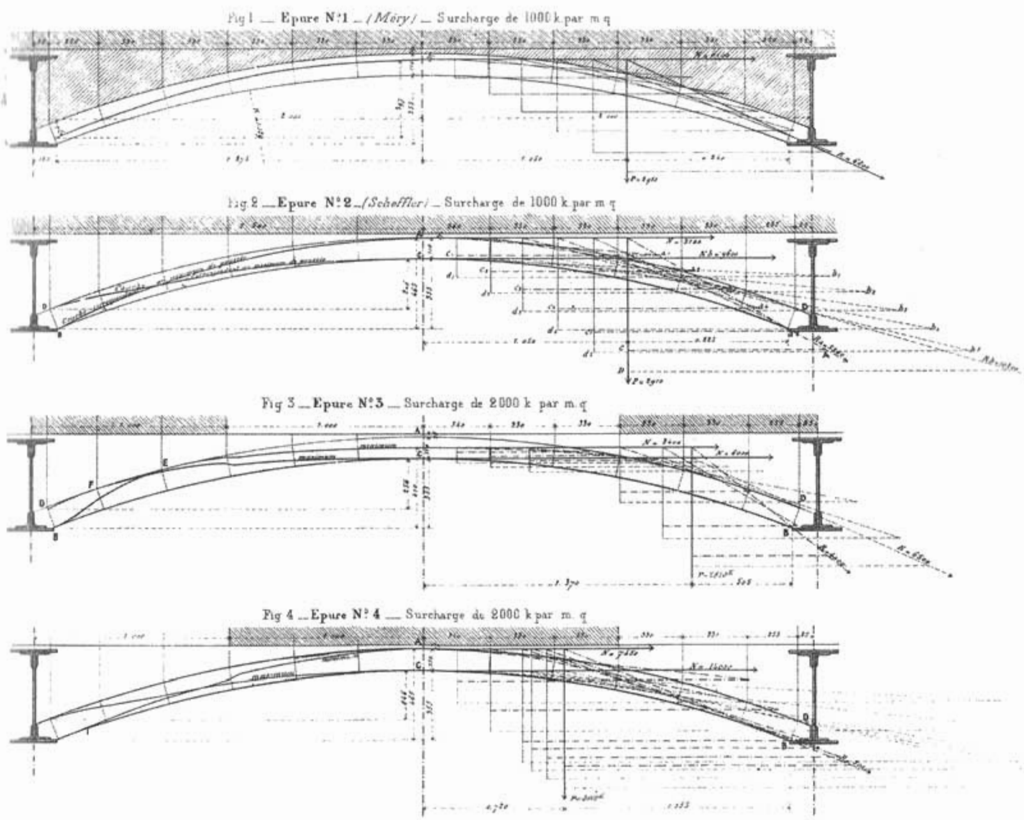

Fig. 6: The different thrust lines shown on the tested vaults (Fontaine 1865, pl 45).

with up to 1000kg/m.^{2}; in a series of adjacent vaults, ties will be required should the loads be greater than 500kg/m.^{2}.

Fontaine devotes the rest of the article to obtaining the thrust generated on the supports by a load of 1000kg/m.^{2}. In order to do this, he applies to various scenarios the concept of *courbes de pression* that he had explained at the beginning (see Fig. 6): For a uniform load of 1000kg/m.^{2}, he applies what he calls Méry's theory that involves forcing the thrust line to be contained in the middle third of the vault,[17] and he draws the maximum and minimum thrust lines, according to Scheffler's theory; For a load of 1000kg/m.^{2} applied in a non-uniform manner [concentrated first on the sides, and then around the axis of the vault], he again draws the minimum and maximum thrust lines. He did not use the thrust values to obtain any information about the type or size of the supports, although he concludes the article by saying he will continue his work in the future.

Throughout the 19th century, numerous tests on tile vaults were conducted. This fact shows that this construction system was booming and it was necessary to offer certain guarantees in a moment when it was beginning to be common trend to justify structures with calculations. D'Olivier carried out a very practical test looking for a particular outcome: measuring the thrust in order to prove false the monolithic theory that stated that tile vaults exerted no thrust. From the thrust measured, he obtained the thickness of the wall required to support it. He did not extend his results to other types of vaults, maintaining that, in order to do this, the test could be repeated on the different vaults. Laroque carried out a simple test to check the maximum uniform load that a tile vault can support, obtaining very large values of the collapse load. Fontaine wanted to obtain the maximum loads that can be supported by a vault of four m. span and 1/10 rise, resting on metal beams, with the purpose of building a large floor surface using this type of structure. He tested a number of similar vaults, under both uniform and asymmetric loads. Fontaine did not experimentally measure the thrust, but set its bounds drawing the maximum and minimum thrust lines inside the vault. However, despite the results of the test proving without any doubt that tile vaults exert thrust, the monolithic, no-thrust theory, continued to be cited in construction and engineering manuals. Builders and architects continued, nonetheless, to provide buttressing when building this type of vaults.

Acknowledgements

The help of Prof. Santiago Huerta, my thesis supervisor, has been essential for the preparation of this paper. He has been permanently available to answer my numerous questions. Furthermore, he has given me many interesting ideas and references to frame the current subject.

Notes

1. Compilation of articles about tile vaults in Huerta (2001). For the historic development, see Mochi (2001) and Tarragó (2001). For the structural behaviour and the myth of monolithism, see Huerta (2003). A bibliography on tile vault construction can be found in Huerta, López and Redondo (2001) and Ochsendorf (2010). For masonry shell theory, see Heyman (1977).

2. See Guastavino (2006) about his tests. Huerta (2003) offers a thorough analysis of them. An essay written in England is described in Cubbit (1841). The Spanish essays are described in (Resistencia de bóvedas tabicadas, 1892).

3. Tavenot, in 1747, presented a memoir to the Académie Royale d'Architecture about traditional tile construction in the French Roussillon. Blondel attended this presentation. In 1754, the count d'Espie wrote his book on fireproof flooring structures. Finally, Blondel included this construction method [both the traditional method of Roussillon and those proposed by Espie] in his treatise *Cours d'Architecture*. Later on it was also included in Rondelet's *Traité de l'art de bâtir* (Huerta 2003).

4. The matter of the expansion experienced by the plaster as it sets and its influence on the increase in thrust of tile vaults is a recurrent theme from the end of the 18th century. Blondel (1771) defended that this is the only reason for the thrust of tile vaults "6º De pendre des précautions contre l'action du plâtre (…) : alors la voùte PQ ne feroit exactement que l'office du couvercle d'un pot, & la poussée contre ses murs T, ne feroit pas plus considérable que celle d'un plancher ordinaire" (Blondel 1771, 6: 119).

5. "Les voûtes les plus en usage aujourd'hui, sont celles en briques et ciment romain ou plàtre" (Lagarde 1849, 97). "L'usage des briques pour la construction des voûtes d'une grande portée et d'une très-faible épaisseur est devenu très-fréquent, depuis qu'on possède les mortiers de ciment romain pour en effectuer la liaison" (Claudel and Laroque 1870, 470). In Claudel and Laroque (1870, 472-475) many buildings featuring tile vaults are described, some of which were built by the authors.

6. It appears that collapse occurs by "snap-through," due to a large spread of the supports.

7. Before 1837, various authors [Couplet, Danzy, Coulomb, Audoy] had explained the failure process of vaults by the formation of hinges described by d'Olivier in his essay. However, he seems to be the first in trying to experimentally measure the thrust of a vault, rather than obtaining it analytically. Leonardo da Vinci, in the Codex of Madrid, drew a number of mechanisms aimed at measuring the thrust of vaults, but there is no evidence that he ever built them (Zammation 1981).

8. The tensile strength of masonry depends heavily on the adhesion between the blocks and the mortar. This value is particularly high between bricks and plaster. Guastavino, in later experiments, obtained similar tensile strengths of 20kg/cm^2 (Huerta 2004).

9. To draw the thrust lines, a weight of 90kg has been considered for each half of the tested vault. This datum is not given by Olivier in his essay, but appears in later references to his work (Lagarde 1849, Claudel and Laroque 1850). It is equivalent to a specific weight of 1530kg/m^3.

10. In order to draw this new geometry, we draw a line joining the hinge at the crown with one of the hinges at the springing. This line rotates, but the length remains constant as the vault deforms, so that, the descent of the crown being known, it is possible to work out the spread of the supports (Huerta and López 1997).

11. "M. D'Olivier n'a pas fait d'expériences sur des voûtes plus épaisses ni d'un plus grand diamètre" (Lagarde 1849, 98).

12. A « roman » type of cement [fast hardening], produced in Yonne (Claudel and Laroque 1870).

13. Claudel and Laroque give a failure load for the brick between 90 and 150kg/cm², and of 155kg/cm² for the Vassy cement. The combined strength of the masonry is smaller. In the 19th century it was common to design for 1/10 of the failure load (Huerta 2004).

14. Fontaine mentions twice throughout the text the reason for performing his tests: "Chargé de faire une étude qui devait servir de base a l'etablissement de 72000 metres carrés de planchers" (Fontaine 1865, 149); "Les 72000 metres carrés de planchers que nous construisons sont formés d'une succession de voûtes plates de 4 mètres de portée reposants sur des poutres flexibles. On comprend, d'après cela, l'interêt considérable qui s'attachait á cet essai" (Fontaine 1865, 152).

15. In Heyman (1982), Huerta (1996) and (2004) a full explanation of vault theory is provided.

16. The Burgundy brick was commonly used in Paris. Its size is 22x11x 5cm, smaller than other bricks used throughout France (Claudel and Laroque 1870).

17. This way, and following Navier's law that relates stresses and deformations, the development of tension stresses in the vault is prevented.

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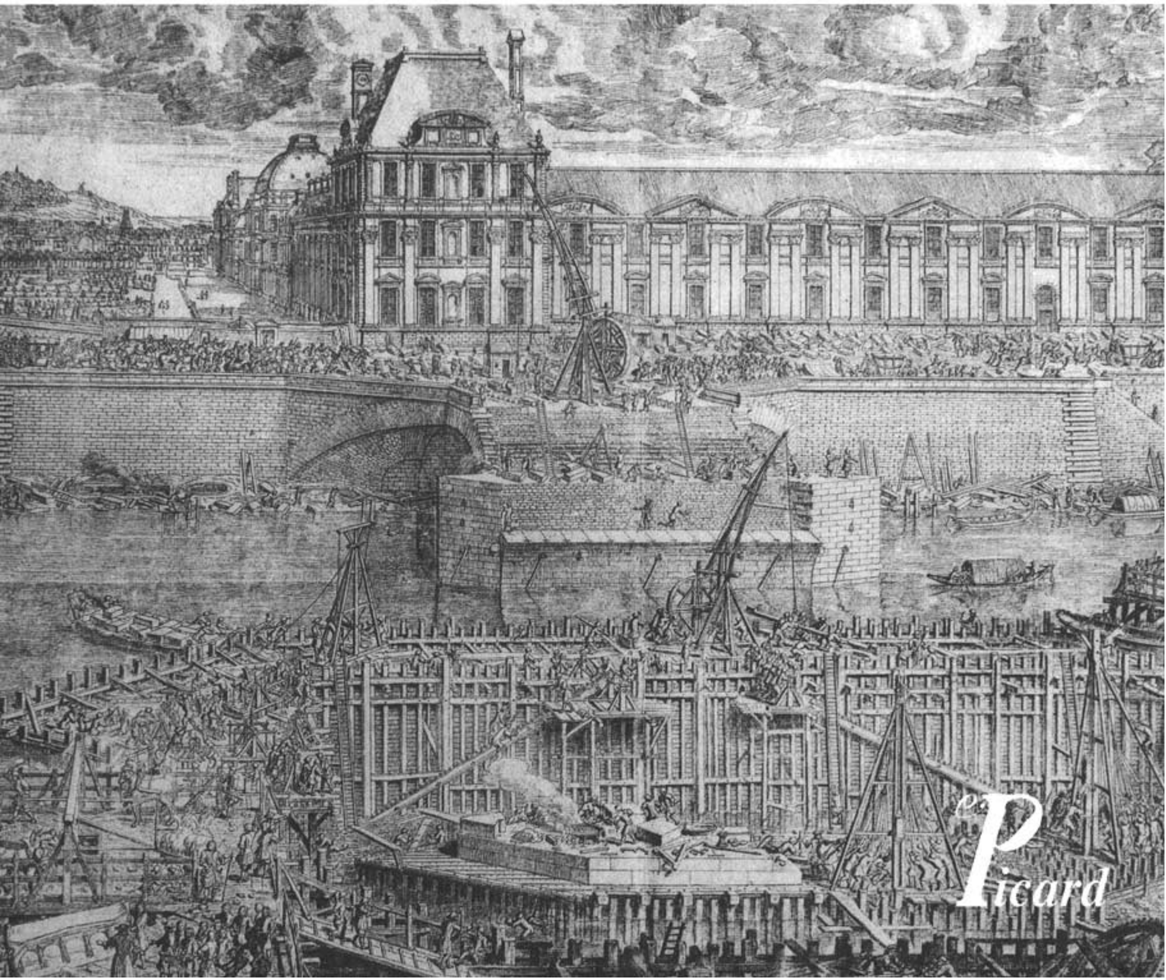

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